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ABSTRACT

Seven experiments were run to determine the precise nature of some of the variables which affect the processing of short-term visual information. In particular, retinal location, report order, processing order, lateral masking, and redundancy were studied along with the nature of the confusion errors which are made in the full report procedure. All seven experiments were carried out with a tacistoscope and display durations were kept at 200ms or less. In six of the experiments stress was placed on having the subjects process in a known order. In five of the experiments retinal location was varied independently of processing order. The results of the experiments led to the following conclusions: (1) retinal locus is an important variable; (2) processing order is an important variable; (3) stimuli inhibit other stimuli at the sensory level and the inhibition appears to be directed from the stimuli toward the fovea; (4) letters are processed at the feature level and some features are more important than others; and (5) no acoustic confusions are made in the full report procedure. (Author)

Final Report

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OPTIMAL MIXTURES OF TEST TYPES IN PAIRED-ASSOCIATE LEARNING
(Sensory Information Processing)

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Preface

All of the research in this final report was carried out in association with Samuel Hollingsworth, a graduate student at Dartmouth College. His ideas and efforts were critical in all seven experiments.

The report was written while the author was at the Center for Human Information Processing at the University of California, San Diego. The center (under partial support from NIMH grant MH-15828) was generous in its assistance.

Table of Contents

List of Tables

List of Figures

Background

Much of our daily activity requires the extraction of information from visual displays. Reading is one of the most important examples of the extraction process. In reading we translate a white page full of black lines and squiggles into letters, words, phrases, and finally into ideas, impressions, and feelings. Reading is at the very core of the educational process, being the vehicle for information transmission in most, if not every subject matter.

Cognitive psychologists view the reading process as the passage of information through a series of different memory stores with a variety of transformations taking place between the various stores. A simplified and schematized version of these stores and transformations is presented below. The system is similar in many respects to the one described by Atkinson and Shiffrin (1968).

The sensory input from the visual display is initially stored as a series of features in a transient register often refered to as the sensory information store (SIS). The information in this store is available for about 500ms for further processing in the absence of interfering activity. The capacity of SIS is a controversial issue and will be discussed in the introduction to Experiment 6. Some sort of pattern recognition takes place on the features in SIS and the results of the pattern analysis are transferred to short-term memory (STM). Even though the information in SIS was visual the representation in STM appears to be acoustic (i.e. based on the sounds of the letters and words rather than their visual characteristics) (Conrad, 1964). STM is also a transient store with the capability of preserving information for about 30 seconds. Unlike SIS, however, STM appears to have at its disposal several control processes which influence the flow of information. For instance, if the information in STM is consciously rehearsed it can be preserved in STM indefinitely. This allows us to attend selectively to information by rehearsing only that information that we want to preserve. Capacity in STM is limited to about seven letters or comparable chunks (Sperling and Speelman, 1970). A chunk is a well learned unit such as a common one syllable word. While information resides in STM it is continually being transferred to long-term memory (LTM). The longer information resides in STM the more strength it builds up in LTM. The information in LTM is usually encoded in some semantic form. Often only the essential meaning of a series of inputs is stored and the surface details are often left by the wayside. LTM is probably of unlimited capacity. The system just described is speculative in nature but evidence for each of the component parts is building up in the literature. Clearly in order to understand the reading process, the entire system needs to be understood.

Our aim in this research is to achieve a better understanding of SIS and the variables which influence what gets into and out of SIS. We believe that many of the difficulties which occur in the reading process have their locus at this stage of the system.

SIS is usually studied with the aid of a tachistoscope (a device for presenting visual displays for very brief durations). Display durations are usually kept under 250ms. The brief durations are used to prevent eyemovements. If we used long exposure durations and permitted eyemovements we would have a continual flow and mixing of inputs in SIS from a variety of visual stimuli. The brief displays allow us to freeze the process and examine the fate of the information from a single glance.

Sperling (1960) was one of the first investigators to postulate the existence of SIS. Many previous investigators had found that if you present different numbers of letters to subjects in a tachistoscope the number reported increases with the number presented up to about four letters. Further increases in display size do not produce increases in the number reported. This asymptote of four was interpreted as the number of letters which could be perceived in single glance. Sperling believed that we could "see" more than four letters but that there was some bottleneck further upstream which prevented subjects from reporting more letters. Several investigators have suggested STM as the probable bottleneck. Sperling developed the partial report procedure to test his hypothesis. Subjects were presented with rows of letters in a tachistoscope. Subsequent to the termination of the display a tone was presented to the subject indicating which row of the display was to be reported. This partial report reduced the strain on STM and produced much higher estimates of the amount "seen" in a single glance. He also found, however, that the signal was only effective if presented within 500ms of the offset of the display. He reasoned therefore that there must be some fairly literal sensory register where visual information is preserved for about 500ms.

Considerable research on SIS has followed Sperling's seminal experiments. Much of the research, however, has focused on rather obscure theoretical issues. The predominate issue in this research is the question as to whether processing in SIS takes place in serial or parallel. Townsend (1971) has demonstrated formally that this issue may, in fact be unsolvable. Relatively little attention in the last decade has been directed toward the understanding of some of the more obvious variables of the physical stimulus which might affect processing in SIS.

In a typical SIS experiment a subject is asked to begin each trial by fixating on a small dot or spot of light in the tachistoscope. Fixating causes the subject to adjust his line of sight so that the dot is located in the center of the fovea, the point of maximum visual acuity. A display containing some number of letters is then presented for a brief duration in the same visual plane as the fixation dot. The subject's task is to report all of the letters (full report), to report a subset of the letters (partial report), or to identify which of a set of target letters was present in the display (detection). The different reporting procedures affect performance and will be discussed at greater length in Experiment 6. In addition to these task variables a number of display and subject variablé "s" also affect performance in SIS. These variables include the retinal location of the letters (Estes and Wolford, 1971); the order in which the letters are reported (Estes and Wolford, 1971); the order in which the letters are processed (Shaw, 1969) and the number and proximity of surrounding letters (Shaw, 1969). A major difficulty in trying to determine the importance and quantitative nature of these variables is that in many experiments they are highly confounded. For instance, in a typical experiment a string of letters might be presented to the right of the fixation point. Letters on the right end of the string will usually be reported less often than letters on the left. The righthand letters are further away from the center of the fovea than the lefthand letters and they are also further out in the processing

8

and report orders. Any of these variables might have been responsible for the decline in performance.

Most of the experiments in this series will attempt to unconfound the various variables and look at the effect of each one in isolation. The final goal is to develop a formal model of how the various variables act and interact. It is hoped that an understanding of these variables may aid us in localizing some of the difficulties encountered in the reading process and possibly to lead to improvements in the physical design of textual material.

Experiments 1 and 2 isolate the function of retinal location and the interaction between retinal location and report order. Experiments 3 and 4 attempt to determine whether processing order independent of report order is an important variable. Experiment 5 looks at the influence of the spacing of letters in a display. Experiment 6 tries to determine the nature of the performance limitation in the full report procedure. Experiment 7 is somewhat tangential to the mainstream. It explores the effect of redundancy in the full report procedure.

9

Retinal Location

It is a well established fact that acuity is not constant over the entire retina. There is ample physiological support for this as the density of cones (the receptors responsible for fine vision) drops off rapidly from the center of the fovea. It is also possible to demonstrate the lack of acuity in the periphery by trying to read out of the corner of your eye. Nevertheless, several investigators have reported evidence that retianl location was not an important determiner of performance in letter recognition (Bryden, 1966; Crovitz and Schiffman, 1965). One problem with these studies is that the report and processing order "s" are not known in advance and may be confounded with retinal location. The first two experiments look at retinal locus without the confounding of report order.

Experiment 1

In addition to exploring the effect of retinal locus in isolation the first experiment examines the interaction between retinal locus and report order. Several experimenters have suggested that retinal locus is only an important variable in interaction with string position (Estes and Wolford, 1971; White, 1970).

The basic design of the first experiment is to instruct the subjects to process and report in a known and consistent order and to vary the retinal location of the strings. Horizontal arrays of letters are presented at a variety of locations with respect to the fixation point. Subjects are instructed to always report and process in a left-to-right order. This unconfounds retinal locus from report order because when a string is presented to the right of the fixation point, letters on the right of the string will be far out on the report order and far away from the center of the fovea; but when the string appears to the left of the fixation point, letters on the right of the string will be far out on the processing order but close to the center of the fovea.

Method

Subjects and apparatus. Twelve Introductory Psychology students from Dartmouth received course credit for their participation in the experiment. All had normal or corrected normal vision and none wore contacts.

The stimulus materials were presented in a Scientific Prototype three channel tachistoscope (Model GA) that was modified with a rapid card changer on two of the channels. Character strings were presented along the horizontal median of a lighted rectangular field which subtended a visual angle of 7.82 degrees in width and 1.68 degrees in height. One field (the fixation field) contained a circular black fixation point measuring 0.073 degrees in diameter centered with respect to the rectangle described above. The luminance of the fixation field was 1.42 ft. lamberts and the luminance of the stimulus field was 1.60 ft. lamberts. The fixation field was visible at all times except during the presentation of the stimulus field. The total illumination in the laboratory was provided by two seven watt bulbs shielded from the subject. Essentially the same apparatus was used in all seven experiments and only changes will be mentioned in the method section of the remaining experiments.

Design and procedure. Thirty nine-letter character strings were generated at random without replacement from the 20 consonants (excluding Y). The character strings were typed in Royal Bulletin typeface on 5 x 8 in note-cards. The entire string subtended a visual angle of 1.89 degrees. A stimulus card was made for each string at each of 18 possible starting positions. The starting position (the position of the leftmost letter) varied from 12 typewriter spaces to the left of the fixation point to five spaces to the right of the fixation point. One display began at the fixation point. Twelve typewriter spaces corresponds to a visual angle of 2.56 degrees. The remaining letters of a string always appeared in consecutive typewriter spaces. Subjects were instructed to begin each trial by fixating on the dot. Once the dot was in focus they were to press a start switch which initiated a 200 ms exposure of the stimulus card. Subsequent to the termination of the display, they were to orally report all of the letters they could in a left-to-right order, trying to always get the leftmost letter correct. This latter instruction was to insure a left-to-right order. Subjects were reminded of the instructions if they missed more than three leftmost letters in any 15 trial block. Each subject saw a random one third of the 540 stimulus cards. A session lasted approximately one hour.

Results and Discussion

The primary results are portrayed in Figure 1. Each point in the figure is based on 120 observations. The graph contains a separate line for each of the different report orders. In other words all of the points in the top line (p = 1) represent the leftmost letters of the 18 different strings. The lines for report orders 5, 6, and 8 have been omitted for clarity. For any given line all of the points on that line differ only in retinal locus. The shape of the line is the shape of the retinal function. Except for orders 1 and 9 all of the orders have roughly the same shape and indicate a steep drop in acuity as you move away from the center of the fovea. The difference between the lines is a function of report and processing order (the two are purposely and perfectly confounded in this experiment).

An analysis of variance was run on the data using ten different retinal locations (-4 to +5) and all nine report orders. The other retinal loci were omitted because they were not represented by all possible report orders. For instance retinal locus -12 is only represented by report order one. Retinal locus led to an $F(9, 99) = 30.3$ and accounted for 9% of the variance. Report order yielded an $F(8, 88) = 72.4$ and accounted for 57% of the variance. The interaction of the two had an $F(72, 792) = 4.5$ and accounted for 3% of the variance. All F's were significant beyond the .05 level. If you remove the first and last report orders from the analysis the order effect becomes somewhat weaker and the interaction essentially disappears. The aberance of the first and last orders will be discussed at length in Experiment 5. It would appear that retinal locus does have quite a strong effect in isolation Report plus processing order has a very pronounced effect and the interaction is relatively weak--by no means the whole shooting match as suggested in some earlier studies.

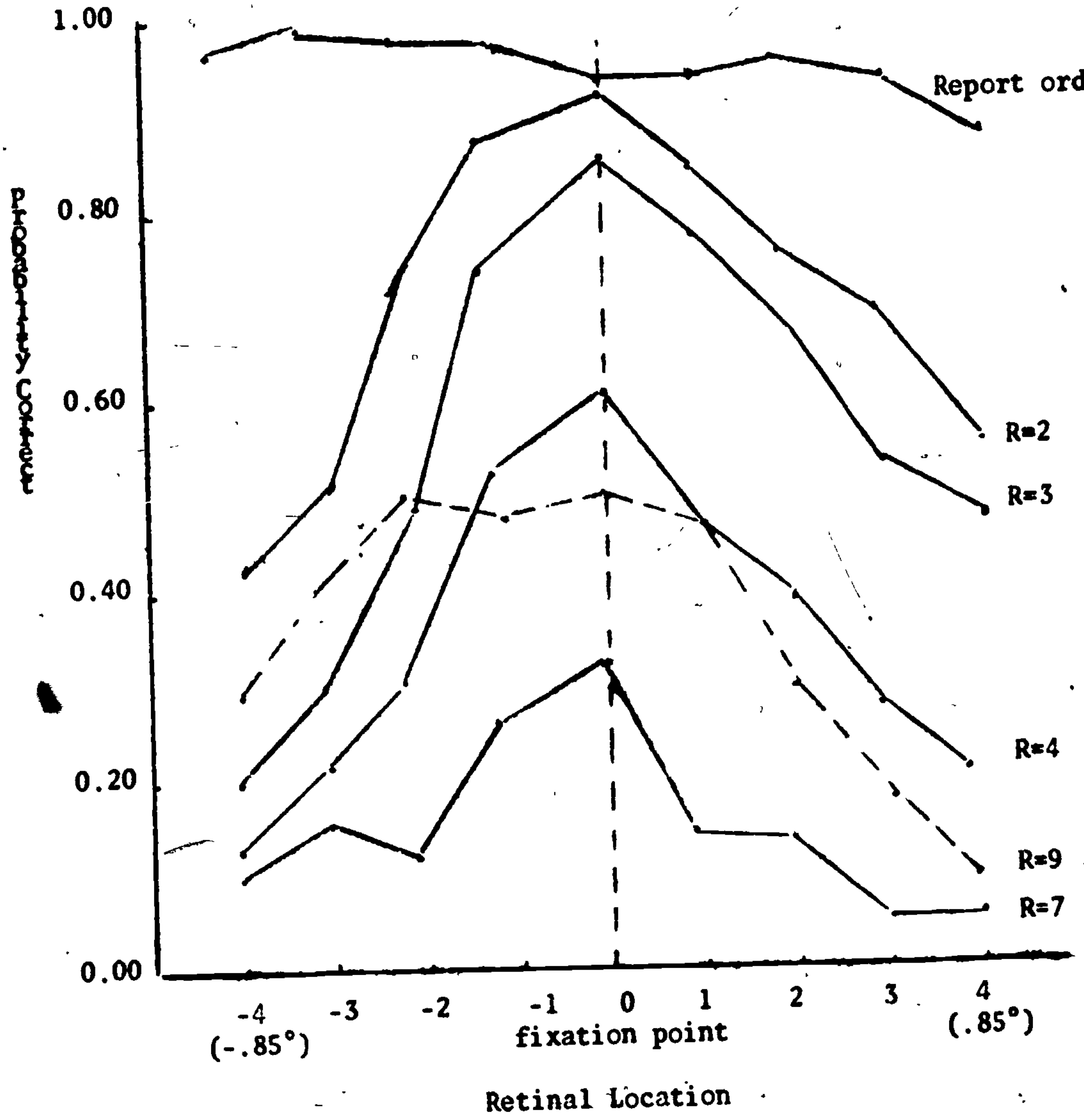

Figure 1. The probability correct as a function of the retinal location of a letter and its processing plus report order from Experiment 1.

Experiment 2

The second experiment attempted to examine the retinal locus function in the simplest possible way. This was accomplished by presenting single letters to different parts of the retina. The presence or absence of a lateral mask was also varied to examine the interaction of retinal acuity and masking.

Method

Subjects and apparatus. Eighteen subjects similar to those in Experiment 1 were used. The apparatus was the same except that the experimenter entered the subject's responses into a portable teletype connected to the Dartmouth time-sharing system rather than recording them on paper.

Design and procedure. The experimental design consisted of the factorial combination of four display types with five retinal loci. The four display types were: single consonant (C); a vowel-consonant diagram (VC); a consonant-vowel diagram (CV); and a vowel-consonant-vowel trigram (VCV). The five retinal loci for the consonants were -2.56, -1.28, 0, 1.28, and 2.56 degrees of visual angle from the center of the fovea. Minus numbers refer to the left visual field.

The target letter on a given trial was one of the eight consonants: C, F, H, J, K, P, Q, or V. The vowel in every case was the letter U which had proved an effective mask in a pilot study. Each of 20 experimental conditions was reproduced for each of the consonants, making a total of 160 stimuli. Each subject received a random permutation of all 160 stimuli. The letters were typed in Royal Bulletin typeface as in all of the experiments.

Each subject participated in one 45 minute session. When he arrived, he read a typewritten paragraph instructing him to fixate on the dot in the center of the fixation field and to press a start switch when the dot was in focus. Stimuli were exposed for 40ms and the subject was to report the consonant on each trial, ignoring the U's, if any. The subject was given feedback on his accuracy every 20 trials.

Results and Discussion

The proportions of correct responses for each of the twenty conditions are presented in Table 1. Each point is based on 144 observations. Chance performance would be 0.125. There was a pronounced effect of retinal locus for each of the display types as indicated by the changing proportions within a row. There was also a strong effect of masking as indicated by the changes within a column. The statistical analysis was carried out in such a way as to emphasize the asymetries between the VC and CV conditions. These asymetries will prove to be of considerable theoretical interest in the fifth experiment.

The analysis was restricted to the VC and CV display types and only the four non-foveal retinal loci were used. There were three factors in this modified analysis: display type (VC vs CV); visual field (left vs right); and, distance from the center of the fovea (1.28° vs. 2.56°). Performance was significantly lower at greater distances from the fovea ($F = 213.69$ with $df = 1, 17$). CV was more difficult than VC ($F = 10.03$ with $df = 1, 17$). The display type by visual field interaction was also significant ($F = 10.07$ with $df = 1, 17$). No other main effects or interactions were significant. The significant interaction means that in the

TABLE 1

Proportion of Co[illegible]esponses From Experiment 2

Display Type	Retinal Locus -12	-6	0	6	12
C	68	91	94	91	69
VC	42	72	90	78	51
CV	41	76	85	67	37
VCV	24	46	84	45	22

left visual field a pre-vowel is more damaging while in the right visual field a post-vowel is more damaging to performance. Another way of phrasing this is to say that peripheral masks are more effective than central masks. Much ado of this finding will be made later in the report.

Processing Order

In Experiment 1 the most powerful effect was provided by the combination of report and processing order. The question remains as to the relative importance of the two variables in isolation. There is considerable evidence in the memory literature attesting to the importance of report order in a variety of paradigms. I, however, can not think of an SIS paradigm for unconfounding processing order and report order or for holding processing order constant while varying report order. On the other hand a number of possibilities exist for holding report order constant while varying processing order. Using these techniques we should be able to decide whether processing order in isolation is an important variable. Shaw (1969) presented evidence that he claimed was in support of processing order as an important variable in an experiment involving SIS. In Shaw's experiment, however, processing order was confounded with retinal location. A number of other investigators have claimed that processing in SIS takes place in parallel (Gardner, 1973; Wolford, Wessel, and Estes, 1969). Processing order should probably not play a major role in a parallel system.

Experiment 3

In this experiment report order is held constant and processing order is systematically varied. The design is similar to the one used in the first experiment. Eight-letter strings were presented at a variety of retinal locations and the subjects were instructed to always process in a left-to-right order. A detection task was used and the position of the target was varied in the processing order. Thus, retinal locus and processing order were unconfounded as in the first experiment and processing order was held constant as a detection paradigm was used.

Method

Subjects and apparatus. Five subjects participated in six sessions each. The apparatus was modified by the addition of a response panel containing four response keys. The response panel was connected to a light panel and to a latency counter. A key press lit the appropriate panel light and stopped the latency counter.

Design and procedure. Two hundred and forty stimulus cards were constructed each one containing an eight-letter string. Half of the strings began with an M and half began with an R. Each string contained one of two target letters (G or H) at one of six possible positions in the string (positions 2-7). The remaining string positions were filled with F's. The strings were placed on the cards such that the leftmost letter varied in retinal location from -8 to +1. This caused the target letters to vary from positions -7 to +7 depending on the position of the target in the processing order. The factorial combination of the ten retinal locations, six positions in the processing order, two initial letters, and two target letters produced the 240 stimulus cards.

The subject was instructed to identify the initial letter and the target letter on each trial as rapidly as possible. There was a single response key for each of the four possible combinations of initial and target letters. The subjects were to press the appropriate key as rapidly as possible on each trial. The latency counter was begun with the termination of the stimulus exposure and terminated with the subject's response. A 50ms exposure duration was used. The subjects participated in six sessions on separate days. They were shown a new random permutation of the 240 cards at each session. Feedback was provided to the subject after every 20 trials. Subjects were instructed to always process in a left-to-right order and to always get the leftmost letter correct. The remaining procedural details were similar to the first experiment.

Results

To preserve the proper counterbalancing the analyses have been restricted to those trials in which the targetletter appeared in retinal locations -2 through +2. Again, these were the only locations represented by all six processing orders. The first session for each subject was also discarded. (The data in a detection task are much less stable than in a report task. Therefore, each subject was run for several sessions and the first, or warmup, day was discarded.) Table 2 contains the proportions of correct responses as a function of retinal location and processing order averaged across subjects. Only those trials in which the initial letter was correctly identified were used. Trials on which the initial letter was incorrectly identified may have represented failures on the part of the subject to process in the correct order. Each proportion in Table 2 is based on 120 observations (6 subjects X 20 observations per subject) which is probably a bit too few to obtain reliable proportions when the probability of a correct response by chance is 0.50.

An analysis of variance was carried out on the data in Table 2 two factors (five retinal locations and six processing orders). Only the main effect of retinal location even approached significance ($F(4, 20) = 2.08$, $p = .121$). All of the remaining F's were less than 1.0. An arcsin transformation on the proportions left the results of the analysis of variance unaffected. The retinal effect might have been significant with more stable data. The processing order function, however, appears almost completely flat.

Table 3 contains the average latencies for those trials on which both the initial and target letters were correctly identified. Analyses of variance were carried out on these raw latencies and on two transformed versions of the data. The first transformation was a correction for guessing that was used in Wolford, Wessel, and Estes (1969). The second version was the logarithmic transformation (a transformation often used in reaction time studies). Fortunately, for clarity sake, all three analyses produced identical patterns of F's. Only the F's for the raw latencies will be presented. The main effect of retinal location was significant ($F(4, 20) = 5.84$, $p<.01$). The main effect of processing order was also significant ($F(5, 25) = 4.90$, $p<.01$). The interaction did not approach significance. A linear trend test on the main effect of processing order was highly significant ($F(1, 25) = 15.15$, $p<.001$) and the linear trend accounted for 92% of the variance attributed to processing order.

TABLE 2

Performance as a Function of Retinal Locus in Experiment 3

Measure	Retinal Locus -2	-1	0	1	2
Proportions	92	94	95	88	86
Latencies	854	831	812	798	811ms

TABLE 3

Performance as a Function of Processing Order in Experiment 3

Measure	Processing Order 1	2	3	4	5	6
Proportions	92	93	90	91	91	88
Latencies	797	801	805	823	841	859ms

The latency data would tend to confirm the results of the first section in finding that retinal locus in isolation is important in determining performance. The latencies also indicate that processing order is a significant effect even in the absence of report order, with the latencies increasing as the target is moved out in the processing order. The discrepancies between the proportion data and the latency data could perhaps be attributable to the instability of the proportion data or the possibility of a ceiling effect in the proportion data. I, however, tend to believe that the discrepancy between the flat function for processing order in the proportion data and the linearly increasing function in the latency data is a real effect and requires explaining. Unfortunately, I don't have any good explanations.

Experiment 4

In Experiment 4 retinal locus and report order were both held constant and processing order was varied in a different way from the previous experiment. The subjects were told which direction to process in at the start of each trial. The first letter in the processing order was repeated elsewhere in the string. The subject's task was to identify the letter subsequent to the repeated letter in the processing order. The distance between the two occurrences of the repeated letter was varied. The target letter appeared at the same distance from the fovea for all processing orders. Thus, report order and retinal locus were held constant and only processing order was free to vary. This experiment has two advantages over the previous one: The probability of a correct response by chance was lower and it was almost impossible to respond correctly unless the string was processed in the correct order.

Method

Subjects and apparatus. Thirteen new subjects were used, one session each. The apparatus was identical to the preceding experiment except that no latencies were recorded and the subjects responded verbally.

Design and procedure. There were 144 strings made up of the four primary letters, M, G, H, and T plus a filler consonant at the end of each string. Each string contained all four primary letters and the primary letter that appeared at the beginning of the string was repeated at another location in the string. The letter which followed the repeated letter in the instructed processing order was referred to as the target letter. Half of the strings were constructed with the target at retinal locus -3 (0.63 degrees to left of the fixation point) and half with the target letter at +3. Half of the strings had the initial letter at the right end of the string and half at the left end. For each of the above combinations the number of letter intervening between the two occurrences of the initial letter varied from 0 to 2. There were, thus, 12 experimental conditions (two processing directions, two visual fields, and three processing distances). A sample of the 12 conditions is presented In Table 4. For each of the 12 conditions each of the 12 combinations of the four primary letters as repeated and target letters was used making the 144 strings. Every string ended with a random noise consonant.

TABLE 4

The Display Types Used in Experiment 4

Processing Order	Retinal Locus -7	-6	-5	-4	-3	-2	-1	0 (fixation point)	1	2	3	4	5	6	7
Left-Right															
0									M	M	H	T	G	F	
1								M	G	M	H	T	F		
2							M	T	G	M	H	F			
0			M	M	H	T	G	F							
1		M	G	M	H	T	F								
2	M	G	T	M	H	F									
Right-Left															
0								F	T	G	H	M	M		
1									F	T	H	M	G	M	
2										F	H	M	T	G	M
0		F	T	G	H	M	M								
1			F	T	H	M	G	M							
2				F	H	M	T	G	M						

The subjects began each trial by focusing on the fixation point. The experimenter then informed the subject whether to process inside out or outside in. Inside referred to the center of the fovea or the end of the string nearest the fixation point. (This instruction has the same effect as asking them to process left and right and appeared simpler to the subjects to understand). Following the processing instruction the subject initiated a stimulus exposure of 200ms duration. His task was to respond orally with the first letter in the instructed processing order and the letter following the repeat of the initial letter. The subjects knew that there were only 12 possible letter combinations which could possibly be correct. Subjects were given feedback on their performance on the initial and target letters every 24 trials. A session lasted approximately 75 minutes.

Results and Discussion

The proportions of correct responses are presented in Figure 2 for each of the 12 conditions. Only the main effects of processing order and visual field were significant. As is apparent in Figure 2 performance decreases with increases in the processing distance. Both the latency data of Experiment 3 and the data of Experiment 4 are congruent in showing that processing order is a significant variable even with report order held constant.

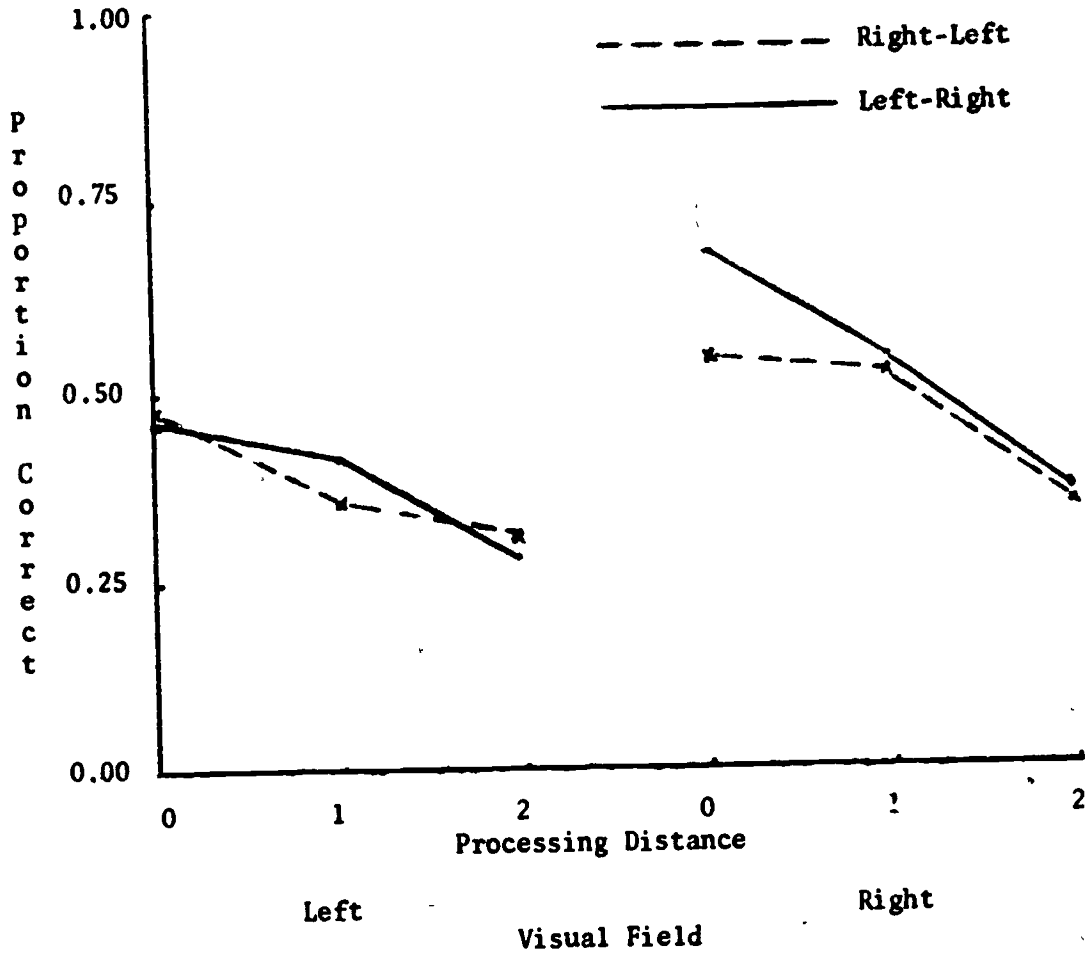

Figure 2. The proportion of correct responses for each of the conditions in Experiment 4.

Lateral Masking

It was demonstrated in the first experiment that the string position of an item was an extremely important performance variable. Report order and processing order have already been considered as likely components of the string position effect. Another factor which varies with string position is the number and position of surrounding letters. For instance both the first and last letter in the string have a blank space on one of their sides. As mentioned in the first experiment the first and last positions were somewhat out of keeping with the other seven positions. It could be that the presence of the blank space was a factor in the performance at positions 1 and 9.

There is evidence in the literature that the presence of a space in a string can have a marked effect on performance. Shaw (1969) introduced spaces into the middle of letter strings and found that a space which followed a letter in the processing order (post space) markedly increased performance on that letter. A space which preceded a letter in the processing order (pre space), however, had little or no effect on the output of that letter. A question of primary importance in the understanding of SIS is whether the space effect is sensory in nature (due to lateral unmasking) or cognitive (based on processing and memory considerations). Shaw believed that the asymmetry between a pre space and a post space implied a cognitive effect. As a further check he ran a similar experiment inserting black rectangles instead of spaces into the strings. The black rectangle produced results very similar to those obtained with spaces. Assuming that black rectangles should be as masking as letters, he concluded that the space effect was cognitive. To be explicit, Shaw assumed that processing involved a two stage serial scanning mechanism where the first stage found material for the second stage to identify. The presence of a space or rectangle gave the second stage additional processing time on the preceding letter because the first stage always moved at a fixed rate. This model explained the asymmetry of the effect and the identity of rectangles and spaces.

At least one study has cast doubt on Shaw's interpretation. Townsend, Taylor and Brown (1971) found a similar asymmetric space effect using very long exposure durations (three seconds) and preventing eyemovements. If the space effect were merely a matter of gaining additional time for the second stage processor, the space effect should have disappeared with the very long exposure durations. Townsend, et. al. proposed lateral masking as the explanation of the space effect. The idea being that letters tend to inhibit adjacent letters at the sensory level. Removing letters from a string reduces this inhibition. They, however, did not deal adequately with the asymmetry or the equality of spaces and rectangles.

A second problem with Shaw's explanation is that processing order and retinal location were confounded in his experiments. A pre space was nearer to the center of the fovea than the letter and a post space was always further from the fovea than the letter. It is possible that the asymmetry is a function of the retinal location of the space with respect to the letter rather than the position of the letter and the space in the processing order.

Experiment 5

The fifth experiment unconfounds retinal locus and processing order in the positioning of spaces. The design is similar to the one used in the first experiment and is also similar to the design used by Estes and Wolford (1971). Basically, strings were presented at a variety of retinal locations and spaces were introduced into some of the strings either before or after the fifth letter in the left-right processing order. A post space was further from the center of the fovea for strings presented in the right visual field (as in Shaw's experiment); but a post space was nearer to the center of the fovea when the string appeared in the left visual field. This experiment differed in at least three important respects from Estes and Wolford (1971): a more balanced design was used, new control conditions were added, and a wider range of the retina was explored.

Method

Subjects and apparatus. Twenty new subjects were run. The apparatus was identical to that used in the second experiment.

Design and procedure. Twleve nine-letter consonant strings (excluding Y) were generated at random without replacement. Five different display types were used along with five retinal locations. The five display types are presented in Table 5. The display types are named with the fifth letter in the string as the referent. Each of the 12 strings and five display types appeared at five different retinal loci with the fith letter appearing at either -1.90, -0.95, 0, 0.95, or 1.95 degrees away from the center of the fovea where minus numbers refer to strings appearing in the left visual field. The factorial combination of the five display types, five retinal locations and 12 strings yielded 300 stimulus cards.

The 300 cards were randomly permuted. One hundred fifty cards were shown to one subject and the other 150 to the next subject. The next two subjects saw the same permutation of the stimulus cards in reverse order and the cards were then randomly permuted again.

A typewritten set of instructions was given to the subject when he arrived. He was instructed to fixate on the dot in the center of the fixation field. When the dot was in focus the subject initiated a 200ms exposure of the stimulus with a hand held microswitch. The subject was to report as many letters as he could in a left-right order. It was stressed that he should try to be always correct on the leftmost letter. He was told to never report any double-A's and was informed that no other vowels would be presented. At the end of every 15 trials feedback was given to the subject. If he missed more than 3 leftmost letters he was reminded of the instructions. A single session lasted approximately one hour.

The purpose of the double-A slides was to control for the report order advantage of pre space slides over post space slides. In other words in addition to any effect a pre space produced due to lessened masking or increased processing time it also moved the fifth letter from fifth to third in the report order. Since subjects were instructed never to

TABLE 5

Retinal Location

fixation point

-10 (-1.90°) -5 0 5 10 (1.90°)

C	F	H	L	T	B	J	Q	V	(control)
C	F			T	B	J	Q	V	(pre space)
C	F	H	L	T			Q	V	(post space)
C	F	A	A	T	B	J	Q	V	(pre A)
C	F	H	L	T	A	A	Q	V	(post A)

report double-A's they should provide the same report order advantage as a space but would have no effect on the amount of lateral masking or processing time.

Results and Discussion

The major results are presented in Figure 3. The results are the proportion of correct responses on the fifth letters for each of the five display types and five retinal locations. The results are averaged across the 20 subjects. An analysis of variance was carried out on the results. Both main effects (display type and retinal locus) were highly significant as was the interaction. The analysis of variance, however, does not seem to be the best way to extract relevant information from this experiment. To look directly at the space effect t-values were computed between the space and corresponding double-A condition at each of the retinal locations. As was expected the pre double-A condition was superior to the control displays at all five retinal loci while the post double-A's were essentially the same as the control displays. The two retinal loci in the right visual field (+5, +10) provide a replication of Shaw's results. Namely, a post space facilitates performance but a pre space is no different than the corresponding double_A display. Therefore, the superiority of the pre space over the control can probably be attributed to a report order advantage. The displays in the left visual field are in direct contradiction to Shaw's results. A pre space was significantly superior to the double-A's and controls but a post space was not. The reversal of the asymmetry between the two visual fields suggests that it is not the position of the space in the processing order which is critical but the relative retinal locations of the space and fifth letter. The lack of importance of processing order implies a sensory explanation of the space effect.

Two further issues need to be resolved: why is the space effect asymmetric and why do rectangles act like spaces. At least two possible sensory explanations appear as possibilities for handling the asymmetries. The first one is that inhibition (or masking) increases as you leave the center of the fovea. This is consistent with available physiological data where the size of receptive field increases as you leave the center of the retina and the amount of neural crosstalk also increases. This increase in inhibition, however, does not account for the asymmetry of the space effect by itself. If we closely examine Figure 3 we notice that the pre space at +10 is ineffective while the post space at +5 is. This is true even though the pre space at +10 is further from the center of the fovea than the post space at +5. This is not to say that inhibition does not increase as you leave the center, it just isn't responsible for the asymmetry.

A second possibility is that inhibition is not symmetric about a letter. If we hypothesize that more inhibition is directed from a letter in the direction of the fovea we can account nicely for the space effect. A pre space in the right visual field is not effective because the letters which were removed were casting their inhibitions toward the fovea and away from the fifth letter. This is only a post hoc explanation but it does fit the data and is supported by the finding that receptive fields tend to become increasingly eccentric as you leave the center of the

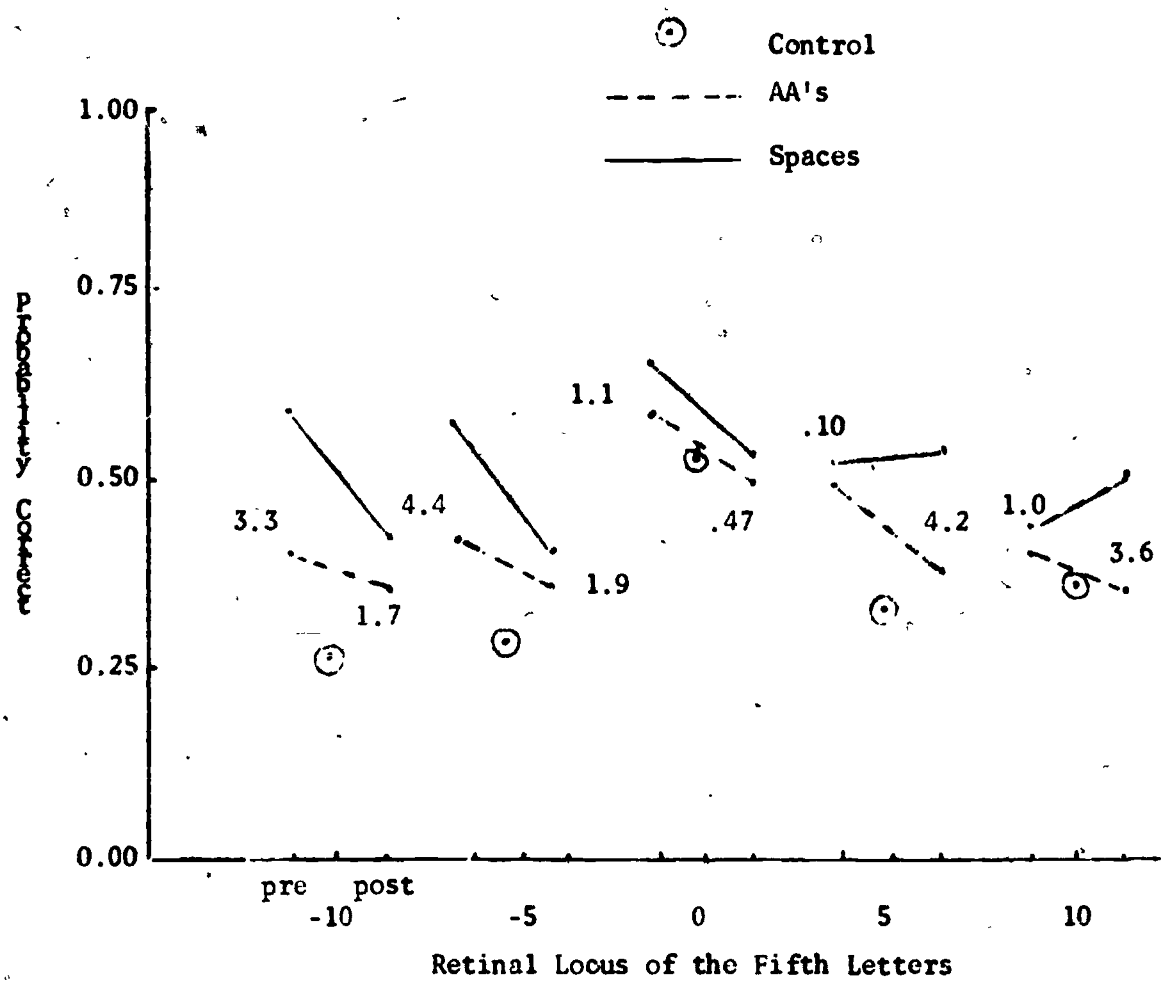

Figure 3. Probability correct on the fifth letters as a function of retinal locus and display type in the fifth experiment.

fovea. An eccentric receptive field would provide the directed inhibition described in the hypothesis above.

The final problem is to suggest how the above sensory explanation could account for the identity of spaces and rectangles. Most single cell recording research suggests that the visual system tends to transform patterns of light into a series of features through the use of receptive fields. For every feature detector there is an optimally shaped stimulus for inhibiting that detector. As a general rule a line detector would be maximally inhibited by adjacent parallel lines, etc. Large areas of uniform brightness would have much less inhibitory influence. Adjacent letters then would provide greater inhibition than either spaces or rectangles.

The data from this experiment suggest that the oddity of processing orders 1 and 9 in Experiment 1 may have resulted from a space effect. The implication exists that important information is more likely to be detected if it has a peripheral space.

Confusions in SIS

The measurement of the span of apprehension (or single look perceptual capacity) had occupied a place in the literature over a considerable time span. The basic finding was that when subjects were asked to report all of the letters from a tachistoscopic display, the number of reported letters increased with increases in display size up to about 4.0 to 4.5 letters. Increases in the display size beyond that point produced no further increment in the number of letters reported. This was believed to represent the limit on the amount of information human observers could perceive in a single look at a visual display.

Sperling (1960) questioned the nature of the performance limitation in this task. He felt that subjects could "see" many more than 4 items in a brief visual display but that their report was limited by a bottleneck further upstream. Sperling and others have postulated that this bottleneck is an overloading of short-term memory (Sperling, 1960). At least two different techniques have been developed which measure processing limitations under conditions which place less of a burden on short-term memory. Sperling (1960) and Averbach and Corriel (1961) developed techniques in which the subject only had to report a limited amount of the information from a display as indicated by an appropriate marker subsequent to the display. In Sperling's partial report procedure this marker was a tone which signalled which row of a matrix was to be reported and in Averbach, et. al. the marker was a visual stimulus which indicated spatially which letter to report. Estes and Taylor (1964) introduced the detection paradigm in which the subject had to determine which member of a predetermined set of targets a particular display contained. All of these procedures greatly reduced the burden on short-term memory and all yielded much higher estimates of the limit of perceptual capacity. The success of these procedures was taken as evidence for short-term memory as the culprit in the full report procedure. These studies, however, do not offer direct evidence for short-term memory overloading in the full report procedure. It is possible that these procedures altered the "perceptual task" in ways which led to the improved performance. This possibility was discussed in detail in Rumelhart (1970).

Experiment 6

The purpose of this experiment is to obtain more direct evidence for the role of short-term memory in the full report procedure. The logic of the experiment rests on the finding that subjects in short-term memory experiments tend to make a substantial number of acoustic confusion errors (Conrad, 1964). Two properties of these confusion errors are also of relevance: the conditional probability of an acoustic confusion given an error is highest at minimal delays (Conrad, 1967), and the presence of acoustic confusions is not restricted to a particular input or output mode (Sperling and Speelman, 1970). For our experiment, then, we presented the subjects with tachistoscopic arrays of letters; we asked the subjects to report as many of the letters as possible; and, we examined the data for the presence of acoustic confusions. There is one problem with the standard full report procedures for our present purposes. When an error is made in the standard full report procedure there is no way of determining what the correct letter should have been because position information is not retained in the response. In our experiment, therefore, the subjects had to report all of the letters presented and to report them in the correct positions. Due to the difficulty of this task the display size was limited to five letters.

Method

Subjects and apparatus. Five persons from the Dartmouth community were paid $2.00 per hour for their participation in the experiment. The apparatus was identical to that used in Experiment 5.

Design and procedure. One hundred sixty five-letter character strings were generated at random without replacement from the twenty consonants (excluding Y). The character strings were typed in Royal Bulletin typeface on while 5 x 8 in. notecards. The entire five-letter array subtended a visual angle of 1.05 degrees. The arrays were positioned on the cards so that the leftmost letter would begin 0.073 degrees to the right of the fixation point and would be located on the same horizontal median.

Each subject received two presentations of each of the 160 stimulus cards over a two day period. A new random order was used for each subject and for each session. A trial sequence began with the fixation field in view and the experimenter saying ready. The subject then initiated a stimulus exposure by depressing a start switch. The stimulus field appeared with no delay for a predetermined exposure followed by a return to the fixation field. Following each stimulus exposure the subject was instructed to verbally report all five consonants in a left-to-right order, guessing if necessary. He was told that only those responses that were output in the correct position would be scored as correct. Subjects were aware of the set from which the letters were drawn and that there were no repeated letters in any stimulus. There was an intertrial interval of approximately 11 seconds. The subjects' responses were entered on the teletype by the experimenter. Feedback was given to the subject after every 20 trials as to the percent correct overall and the percent correct on leftmost letters. The stress on leftmost letters was intended to insure left-to-right processing. The exposure durations were altered on a continual basis for each subject to maintain performance at approximately 60%. Exposure durations ranged between 15-25ms. An experimental session lasted approximately one hour.

Results and Discussion

The overall performance is depicted in Figure 4. Each point is based on 1600 observations (5 subjects x 320 trials). The overall data is scored in two different ways. In the position relevant method an item must be output in the correct serial position to be counted as correct. In the position irrelevant method a letter in the response is scored as correct if it appeared anywhere in the stimulus. Unless explicitly mentioned otherwise only the position relevant scoring method will be used in the analyses to be presented. The probability correct averaged across serial positions is 0.63 for the position relevant method and 0.79 for the position irrelevant method. The serial position curve is U-shaped as in most tachistoscopic experiments.

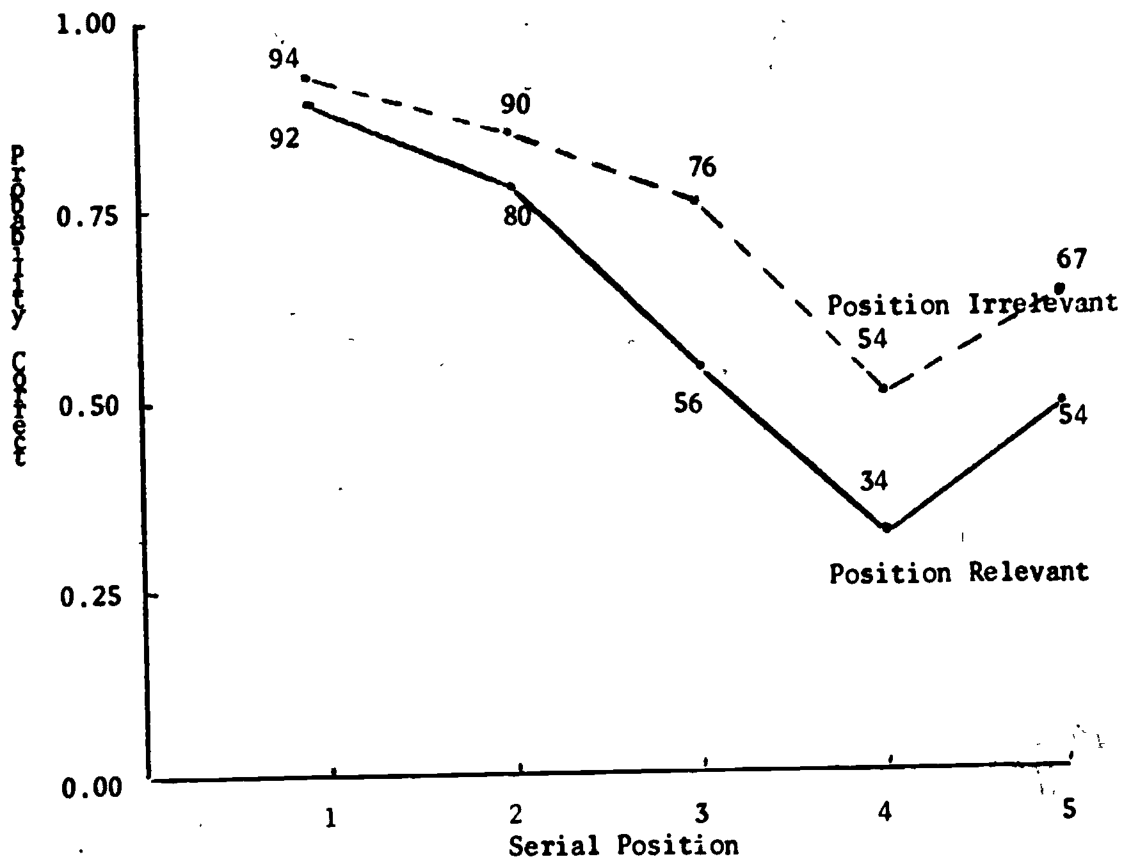

Figure 4. The probability correct as a function of serial position for Experiment 6.

In order to determine the nature of the confusions in this experiment we need some idea of the nature of relatively "pure" visual and relatively "pure" acoustical confusions. We used data collected by Wessel for this purpose. Wessel had 47 subjects sort the letters of the alphabet twice: once on the basis of visual similarity and once on the basis of acoustic similarity. The data were clustered using Johnson's nonmetric clustering procedures.

To determine the nature of the confusions in this experiment, we constructed a visually confusable alphabet and an acoustically confusable alphabet as shown in Table 6. The alphabets were constructed by drawing a line across the two clustering analyses of the sorting tasks at a diameter of 9. Any items which were clustered above that level were placed on the same row of the alphabet. We then defined a confusion as one which came from the same row of the alphabet as the correct letter. To make the two alphabets mutually exclusive, we deleted any pair as a confusion which appeared in the same row of both alphabets. Therefore, outputting M when N was correct would not be scored as a confusion error, if, however, W was output for N it would be scored as a visual confusion. Using this procedure we can partition all errors into three mutually exclusive, exhaustive categories: visual confusions, acoustic confusions, and other. We can also derive the probabilities that a purely random response will fall into one of the three categories given that an error was made. These conditional probabilities are 0.15 for visual confusions, 0.16 for acoustic confusions, and 0.69 for other. Figure 5 shows the observed conditional probabilities of the error types as a fucntion of serial position. The horizontal lines represent the chance probabilities for the two confusion types. The data for "other" are not presented as they can be derived from the presented data. A separate analysis of variance was run on the visual errors and on the acoustic errors to determine if either set was significantly above chance. This was done by testing the grand mean against the appropriate chance values. The visual confusions yielded an $F(1, 4)$ of 69.4, $p<.01$. The acoustic confusions were slightly below chance and yielded an $F(1, 4)$ of 0.74. In neither case was there a significant effect of serial position. From the F values and the results pictured in Figure 5, it is evident that while visual confusions are quite strong there is absolutely no evidence for the existence of acoustic confusion errors.

TABLE 6

Visual Alphabet	Acoustic Alphabet
SZ	HJK
FHLT	QW
MN VWKX	FSX
CG QJ	L
BDP R	R
	MN
	BDP TVZ CG

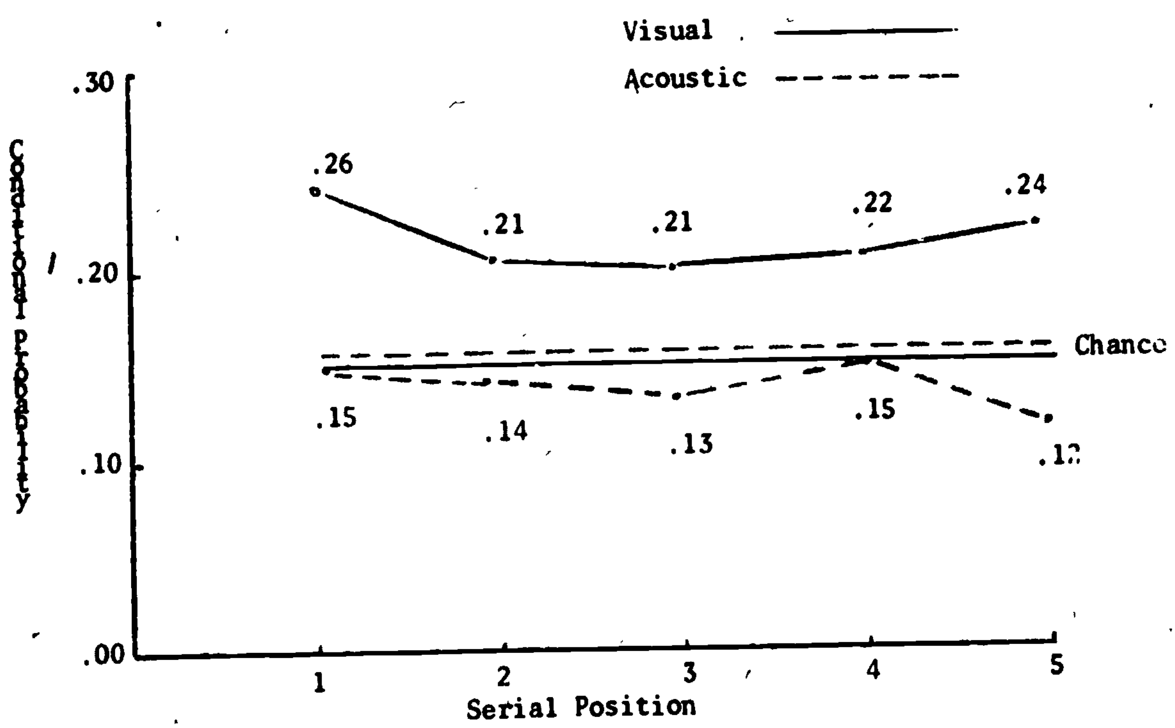

Figure 5. The probability of a visual or an acoustic confusion given that an error was made.

The results described above seem quite conclusive in demonstrating an absence of acoustic confusions in our tachistoscopic experiment using the full report procedure. Our conclusion from these data is that the asymptote of performance in the full report procedure is reached prior to the potential influence of an overload on short-term memory. At least two main issues need to be discussed with reference to this conclusion; what are the possible flaws in our design; and, if short-term memory isn't the culprit in the full procedure, what is?

We believe that a possible flaw in our conclusion is that we may have distorted the ordinary full report procedure in such a way as to produce results which are different from the ordinary procedure. One way to evaluate this is to compare the summary statistics of our data with those of Sperling (1960). The asymptote of performance in Sperling's experiment was reached at a display size of about five and equaled 4.2 letters correct on the average for all display sizes 5 and above. In our experiment the average number of correct letters per trial was 3.3. A large part of the gap between our data and Sperling's is caused by the difference in scoring procedures. If we score our data in a similar fashion (i.e. the position irrelevant method of Figure 1) we find subjects reporting an average of 3.9 items per trial, much more in line with Sperling's data. In fact with a display size of exactly 5, Sperling's sujbects output an average of 4.0 letters. The similarity between the summary statistics between the two experiments leaves us with no compelling reason to believe that our confusion errors would differ substantially from other studies using the full report procedure.

Why are subjects only able to report just over 4 items in the full report procedure when the other procedures outlined in the introduction yielded much higher estimates of perceptual capacity? We lean toward the view espoused in detail in Rumelhart (1970) that the full report procedure differs from detection tasks in the number of features which need to be encoded to insure correct performance; and that it differs from the partial report procedures in the number of letters over which attention must be distributed. It is clearly possible to design a detection task in which the detection of a single feature is sufficient to distinguish the targets from one another and from the noise elements (e.g. V and H as targets and O's as noise elements). In the full report procedure, however, as many as seven features per letter are required to insure correct letter identification (Norman and Lindsay, 1972). It may be that the asymptote in the full report procedure is caused by a limit on the number of features which can be encoded per look. A detection task with this same feature limit could produce much higher estimates of perceptual capacity with the estimation procedures used in those experiments (Estes and Taylor, 1964).

The explanation of superior performance in the partial report is somewhat more controversial. Rumelhart (1970) argues that performance is superior in the partial report procedures because the subject is able to concentrate his attention on a subset of the entire display. The rate at which features are processed is proportional to the amount of attention. In a partial report procedure, then, the subject is able to process more information from the appropriate subset if the cueing signal is presented soon enough subsequent to the termination of the stimulus. Rumelhart's formalization of these assumptions was able to provide an excellent quantitative account for comparisons of the various tachistoscopic procedures. The explanation is controversial because Shiffrin and Gardner (1972) have argued that we do not have control of attention at that level of information processing. Our data do not bear directly on the issue of attention. We do not, however, see any other simple way to account for the difference between the partial and full report procedures, if, as our data suggest, short-term memory is not involved.

An interesting effect was serendipitiously discovered in the data. We first divided the letters into two categories: bilaterally symmetric letters and others. The next question asked was which half of the letter was most critical in the correct identification of the letter. For most symmetric letters either half was equally good (H, M, Q, T, W, Y). J can be correctly identified with the left half but not the right. Most of the remaining letters can only be identified with the right half. These letters include B, C, E, F, K, G, P, and R. For instance with only the left half of the letter present F, P, and R are all identical. The location of these critical features is obviously dependent on the type of font used; so the breakdown will not necessarily apply to other fonts.

We examined the serial position curve for Experiment 6 as a function of letter type (symmetric + J vs. right hand letters). A few of the letters were not included in either pool due to the ambiguity of the critical features. The serial position curves are presented in Figure 6. Quite clearly the increase from positions 4 to 5 is greater for the right hand letters. A t-test was carried out on the amount of upswing for the two letter types. The right letter upswing was significantly greater ($t=8.78$ with 4df, $p<.01$). The letter type difference is consistent with the sensory explanation presented at the end of Experiment 5. Since inhibition is directed primarily toward the fovea the right side of the letters in this experiment receive more inhibition than the left side as all displays are presented in the right visual field. The primary difference between serial positions 4 and 5 is the presence of a space on the peripheral side of the fifth letter. The lessened inhibition on the right side of the fifth letter should be more beneficial to letters which have their critical information on the right side. In addition to supporting the sensory hypothesis this finding has two very important implications: information processing in SIS takes place at the level of features and some features are more important than others.

Due to the interaction of the space effect with visual field as presented in Experiment 5, it would be interesting to examine the letter type difference as a function of visual field. I would predict less of an upswing for either letter type when the last and penultimate letters appeared in the left visual field. We might expect some upswing in the left visual field since the last letter is nearer to the center of the fovea; unlike displays in the right visual field.

To explore the letter type difference as a function of visual field we used the -10 and +5 control displays from Experiment 5. The 8th and 9th letters from these two displays were at roughly similar distances from the center of the fovea. The upswings (probability correct on the oth letter minus the probability correct on the 9th letter) are presented in Figure 7. Zero represents no difference, minus numbers a downswing, and positive numbers an upswing. As is evident in the figure right letters produce more of an upswing and the amount of upswing is greater in the right visual field as predicted. The main effect of letter type yielded an $F(1, 19)=28.06$, $p<.01$; and the main effect of visual field yielded an $F(1, 19)=7161$, $p<.05$. The interaction was not significant. These results offer further support for the sensory explanation presented in Experiment 5.

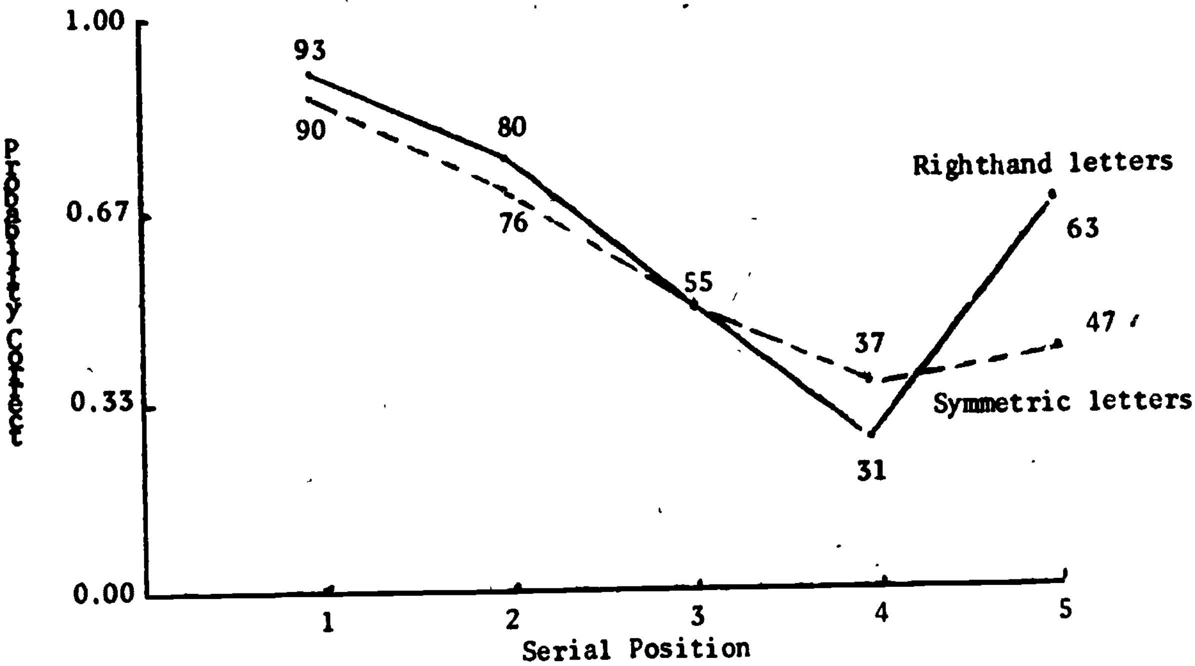

Figure 6. Letter-type serial position curves from Experiment 6.

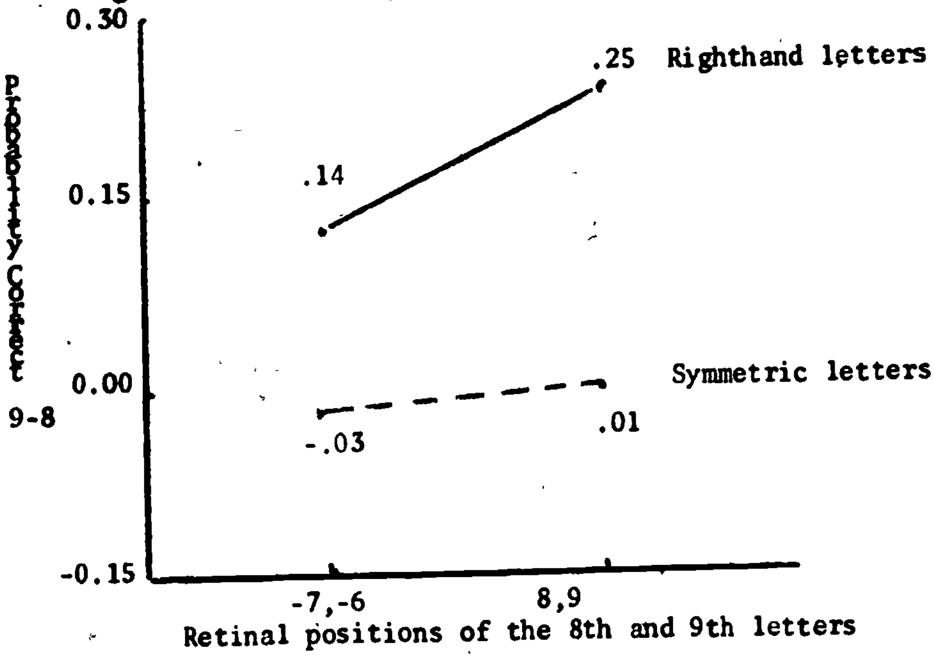

Figure 7. The proportion correct on Position 9 minus the proportion correct on Position 8 from Experiment 5.

Redundancy in the Full Report Procedure

Redundancy has been shown to be an important variable in detection tasks (Wolford, Wessel, and Estes, 1969). Redundancy refers to the repetion of the target letter in a display. Increasing the redundancy increases the probability of a correct detection. Little attention has been paid to redundancy in the full report procedure.

Experiment 7

Five-letter strings were presented as in Experiment 6 except that there were repeated letters in some of the displays. There were two groups of subjects: one which was aware of the double letters and one which was not.

Method

Subjects and apparatus. Two groups of ten subjects each were used. The apparatus was identical to that used in Experiment 6.

Design and procedure. Seventy-five of the displays from Experiment 6 were chosen at random. Twenty-five were left unaltered. In another 25 the letter which appeared at serial position 2 was repeated at position 3. The previous third letter was deleted from the string. Those strings now contained a double letter pair at positions 2 and 3. A similar procedure was carried out on the remaining 25 strings using poisitions 3 and 4.

There were two groups of subjects. One group (Unaware) received the same instructions as in Experiment 6. The other group (Aware) was informed of the existence of the double letter strings. The remaining procedural details were the same as in Experiment 6.

Results and Discussion

The main analyses are presented in Figures 8 and 9. Figure 8 contains the probabilities of getting both of the letters correct which occupied the positions of the double letters. Letters did not have to be output in the correct order to be scored as correct. Figure 9 contains the probabilities of getting at least one of the letters correct from the positions occupied by the double letters. The primary and somewhat puzzling result is that redundancy reduces the probability of a correct response rather than aiding it. This is contrary to detection experiments. The main effect of single vs. double letters for Figure 8 yields an $F(1, 18)=7.78$, $p<.05$ and an $F(1, 18)=13.76$, $p<.01$ for Figure 9. The main effect of position (2 and 3 vs. 3 and 4) is highly significant and would be predicted on the basis of the first four experiments. Neither the main effect of groups nor the interactions are significant. The only explanation which comes to mind is that a letter makes a very good sensory mask for a repeat of itself. The problem would not seem to lie with the decision process since there was no significant effect of groups or interaction with the groups.

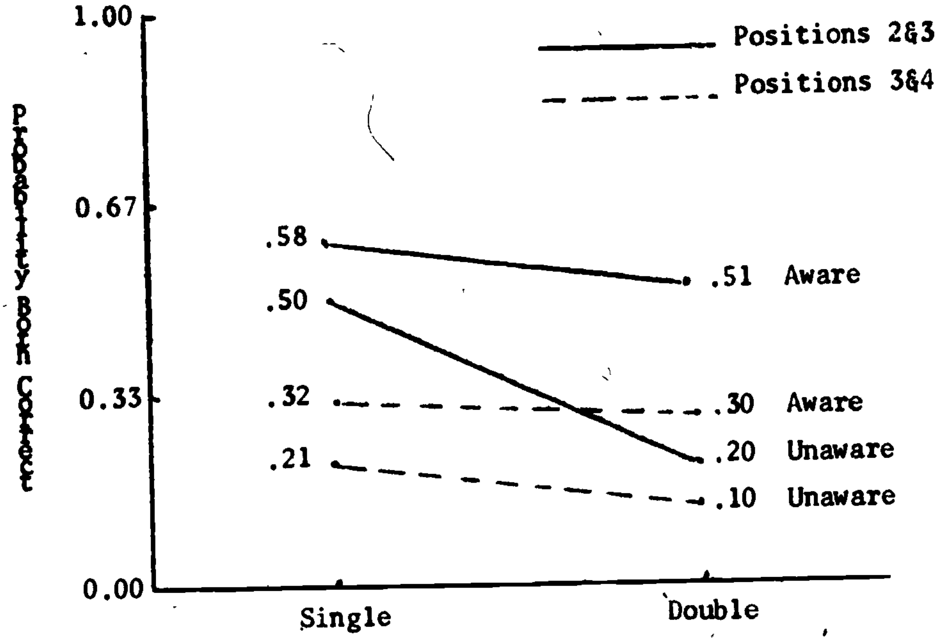

Figure 8. Probability of both letters correct from Experiment 7.

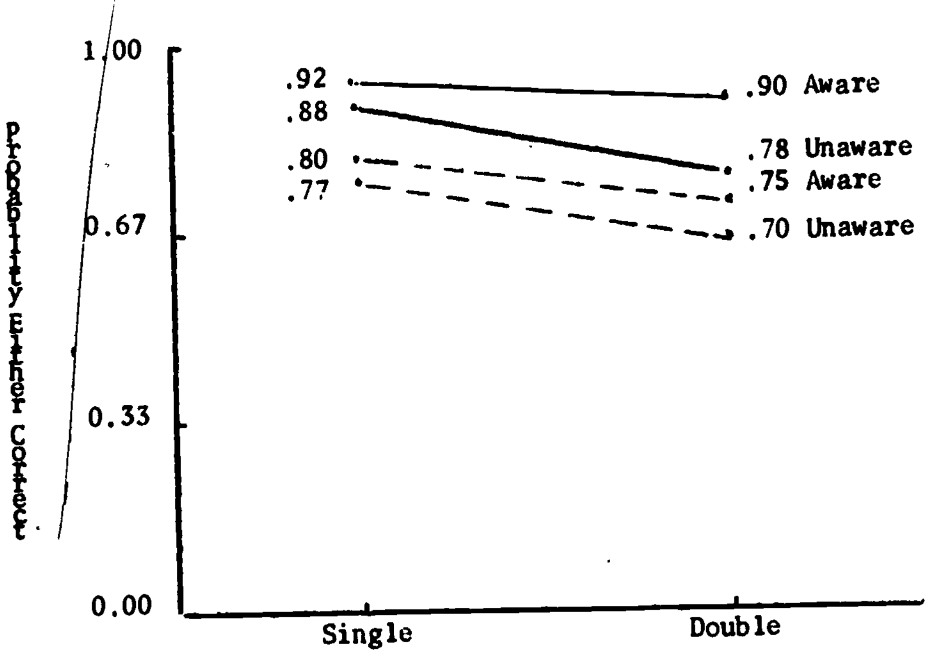

Figure 9. Probability of either letter correct from Experiment 7.

Conclusions

The conclusions for this series of experiments are not fully developed. It is hoped that we will soon have a fully developed formal model which ties the various variables discussed in the experiments together quantitatively. The data appear to be sufficient for the task. Only an insight or two is yet missing.

Several preliminary conclusions can be stated with some confidence: (1) Contrary to earlier findings, retinal locus is an important variable (even in a narrow range around the center of the fovea). (2) Processing is a significant variable in isolation. (3) Report order is probably also important. (4) Stimuli appear to receive sensory inhibition from adjacent stimuli. This inhibition is primarily directed toward the fovea. (5) Letters are processed at the feature level. (6) Not all features of letters are equally important. (6) STM does not appear to be involved in the full report procedure and (8) Redundancy is not helpful in the full report procedure.

All eight of these conclusions are important in understanding the nature of processing in SIS. Conclusions 4-6 may have important practical implications in the understanding of reading difficulties and in the design of fonts and reading materials. For instance letters which often appear at the ends of words ought to have their critical features on the right and spaces should be provided near important materials. The directed nature of the inhibition may have important implications for the reversal errors commonly found in students with dyslexia. It would be premature, however, to formulate any definitive recommendations until a formal theoretical account of the data is completed.

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Appendix

The series of experiments described in this final report is not the same as the series of experiments described in the original proposal. As is explained below one of the assumptions for the proposed research repeatedly proved to be invalid. Since the assumption was crucial to the main experiments in the proposal it seemed wise to discontinue the series. During this time period a secondary line of research in our laboratory was proving quite fruitful. Because the new line of research seemed equally relevant to education we decided to devote our full energies and the resources of the grant to it.

The research described in the original proposal was developed to test the hypothesis that when subjects are required to learn a list of pairs, learning will be optimal if a mixture of Forward and Backward recall tests are used during the learning sequence. This hypothesis was based on four assumptions: (1) forward and backward asscciations grow in a negatively accelerated fashion, (2) Forward recall tests strengthen a forward association more than a Backward recall test would and vice versa, (3) forward and backward associations are independent and (4) different test types use different numbers and kinds of associations. Assumptions 3 & 4 are t[illegible]d in the literature as described in the proposal. The first three experiments in the proposal were designed to test the first two assumptions. The design and results of those experiments are described in detail in the original proposal and in the progress report dated 6/20/72.

The results of those experiments strongly supported the first assumption but cast considerable doubt on the second assumption. Basically, we found that a Forward recall test was more effective than a Backward recall test in strengthening a backward association. Assumption (2) still seemed intuitively correct so we ran a number of pilot studies to see if there might have been a methodological flaw in our procedures. None of these studies, however, yielded any support for Assumption (2). It obviously doesn't make sense to mix test types if Forward recall tests are best for everything.